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Probing the Structure of Nucleons in the Resonance region with CLAS at Jefferson Lab

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The physics of electromagnetic excitation of nucleon resonances, and their relevance in nucleon structure studies are discussed. Preliminary results from the CLAS detector at Jefferson Lab are presented, and future prospects are discussed.

#### 1. INTRODUCTION

Understanding the light-quark baryon spectrum and the electromagnetic transition amplitudes from the nucleon ground state to the excited states provides insight into the spatial structure and the spin structure of the nucleon. In this domain, constituent quarks and glue rather than elementary quarks and gluons appear to be the prevalent degrees of freedom. However, there is evidence that hadronic degrees-of-freedom are important as well, and there exists a well-known phenomenological connection to the valence quark regime in deep-inealstic scattering, known as Bloom-Gilman duality. In order to put the resonance region on the solid footing of QCD, the relative importance of these degrees of freedom as a function of the distance scales must be examined. Photo- and electroproduction of mesons from nucleons provide the most direct information about the spatial and spin structure of the excited states.

The following are areas where the lack of high quality data is most noticeable, and where data from CLAS will contribute significantly.

- To understand the internal nucleon structure, we need to study the full excitation spectrum as well as the continuum. While the continuum has been studied extensively, none of the resonance transitions have been studied well over a large enough distance scale.
- The known spectrum appears rather incomplete when compared with our most accepted constituent quark models [1]. Many states are missing from the spectrum, and some masses of well known states are not well reproduced.
- The role of the glue in the baryon excitation spectrum is completely unknown, although gluonic excitations of the nucleon are expected to be produced copiously

- [2], and predictions of hybrid baryon masses and quantum numbers are available from bag models [3], QCD sum rules [4], and flux tube model [5] estimates.
- The nucleon spin structure has been explored for more than two decades at high energies. The nucleon resonance region which gives dominant contributions to the spin structure functions and sum rules at small  $Q^2$  [6], and the transition to the deep inelastic regime have hardly been explored at all.
- The long-known connection between the deep inelastic regime and the resonance region (parton-hadron duality) [7] remained virtually unexplored in its potential to obtain a better understanding of the nucleon structure.

All these topics are currently studied at JLAB, many employing the CLAS detector [8]. I will focus exclusively on the resonance region and the first preliminary data from CLAS that begin to elucidate some of these aspects of nucleon structure.

# 2. THE QUADRUPOLE TRANSITION TO THE $\Delta(1232)$

The lowest excitation of the nucleon is the  $\Delta(1232)$ , the ground state of the isospin 3/2 spectrum. The electromagnetic excitation is dominanted by a quark spin flip corresponding to a magnetic dipole transition  $M_{1+}$ . This contribution is well known up to fairly large  $Q^2$ . The current interest is in probing the small electric  $(E_{1+})$  and scalar quadrupole  $(S_{1+})$  transitions. These are sensitive to possible deformations of the nucleon or the  $\Delta(1232)$  from spherical symmetry. Contributions at the few percent level to the ratios  $R_{EM} = E_{1+}/M_{1+}$  and  $R_{SM} = S_{1+}/M_{1+}$  may result from interactions with the pion cloud at large and intermediate distances [13,12]. Quark models that include hyperfine interaction from one-gluon exchange predict small contributions as well [15]. An intriguing prediction is that in the hard scattering limit the electric quadrupole contribution should be equal in strength to the magnetic dipole contribution [9]. An analysis [10] of earlier DESY data found small nonzero values for  $R_{EM}$  at  $Q^2 = 3.2 GeV^2$ , showing that the hard scattering limit may be approached only at much larger values of  $Q^2$  than currently accessible.

A recent experiment at Jefferson Lab [11] measured  $p\pi^o$  production in the  $\Delta(1232)$  region at high momentum transfer, and found values for  $E_{1+}/M_{1+} \approx -0.02$  at  $Q^2 = 4~GeV^2$ . The focus with CLAS is on the low to medium  $Q^2$  regime, where data are sensitive to ingredients in nucleon structure models. The  $ep \to ep\pi^o$  is particularly suited to measure the  $N\Delta$  transition multipoles. Complete distributions in the  $p\pi^o$  azimuthal and cms polar angle have been measured over the hadronic mass range from threshold up to W = 1.6~GeV in a range in momentum transfer  $Q^2 = 0.4 - 1.8 GeV^2$ . The data have been analysed using different approaches which give consistent results [16,17]. Preliminary results for  $R_{EM}$  and  $R_{SM}$  are shown in Figure 1 and 2, and compared with recent model calculations.  $R_{EM}$  is small and negative, with a weak  $Q^2$  dependence, while  $R_{SM}$  exhibits a strong  $Q^2$  dependence with a trend towards increasingly negative values. The trend of the data is qualitatively described by quark models that include pion degrees of freedom. These results are in contrast to previous data which show no clear  $Q^2$  dependence of  $R_{SM}$ , and do give ambiguous results for the sign of  $R_{EM}$ .

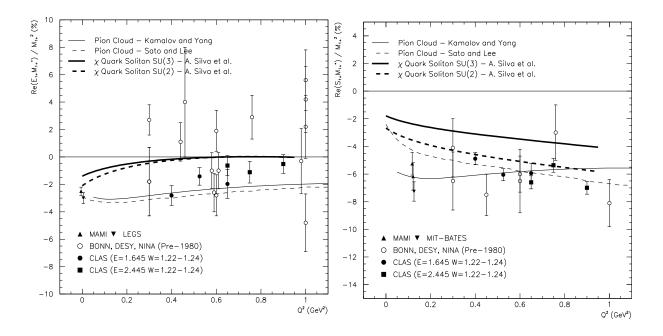


Figure 1. Preliminary CLAS results for  $R_{EM}$  of the N $\Delta$ (1232) transition. The curves represent recent models within a constituent quark model including mesons cloud effects [12,13], and a chiral quark soliton model [14], respectively

Figure 2. Preliminary CLAS results for  $R_{SM}$  of the N $\Delta$ (1232) transition. Same models as in Figure 1.

# 3. WHAT IS SO SPECIAL ABOUT THE ROPER RESONANCE?

The internal structure of the  $N^*(1440)$  has been the subject of an intensive debate in recent years. It is clearly visible as a resonant state in  $\pi N \to \pi N$  and  $\gamma N \to \pi N$  scattering. However, its transition strength drops rapidly with  $Q^2$  in electroproduction [18], and its longitudinal coupling is weak. Neither of these properties is well described in non-relativistic constituent quark models which assign the state to a radial excitation of the nucleon. Moreover, its mass is lower than most models would predict. Models trying to explain these features range from assigning a large gluonic component [19], using lightcone kinematics [21], including strong meson cloud effects [20,22], to describing it as a molecular-type bound system of a nucleon and a  $\sigma$  pseudo-particle [23]. A clear distinction between a gluonic model for the Roper, and meson cloud models, as well as light-cone models, is that the latter ones all predict a zero crossing of  $A_{1/2}(Q^2)$  while the gluonic model does not. Moreover, the scalar amplitude  $S_{1/2}$  should be 0 for a gluonic Roper, while it is large for other models.

Although these models may qualitatively explain the fast drop of the transverse transition amplitude with  $Q^2$ , calculations exist only for the first two models. They make quite distinct predictions regarding the  $Q^2$  dependence as shown in Figure 3. While recent flux tube model calculations [5] give higher masses to gluonic (hybrid) baryons than previous estimates in the bag model [3] and QCD sum rules [4], the Roper could still have a sub-

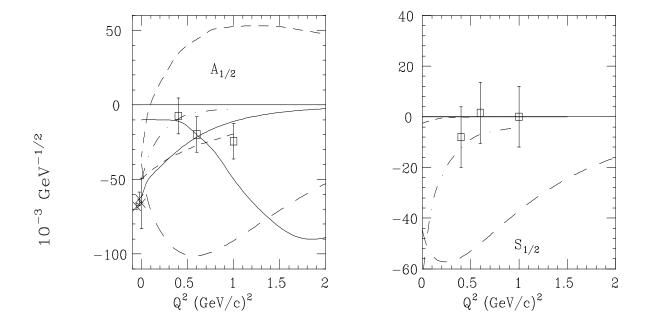


Figure 3. Transition amplitudes  $A_{1/2}$  and  $S_{1/2}$  for the  $\gamma_v pN(1440)$ . The curves are from a quark model using light cone kinematics (dashed), a gluonic excitation model [19] (solid), a non-relativistic dnamical quark model without (long dashes) and with (thin solid) relativistic corrections. The short dashed and dashed-dotted lines represent the boundaries of a fit to the data [18].

stantial gluonic component due to mixing with higher mass gluonic states [24]. Studying these transitions in electroexcitation allows us to probe the internal structure and reveal the true nature of this state. Single  $\pi^o$  and  $\pi^+$  production as well as  $N\pi\pi$  data from CLAS are currently being analyzed to determine the transition amplitudes in a large range of  $Q^2$ .

# 4. HIGHER MASS RESONANCES

The total photoabsorption cross section shows only 3 or 4 enhancements; however, more than 20 states are known in the mass region up to 2 GeV. By measuring the electromagnetic transition of many of these states we obtain a more complete picture of the nucleon structure, and provide the basis for testing symmetry properties of resonance transitions and the underlying 3-quark symmetry group structure. For example, the approximate SU(6) symmetry of the non-relativistic symmetric quark model predicts relationships between transition amplitudes of states belonging to the same  $SU(6) \otimes O(3)$  supermultiplets. For example, in the single-quark-transition model (SQTM), only one quark participates in the interaction. The model predicts transition amplitudes for a large number of states based on a few measured amplitudes [26]. At the photon point the symmetry relations are in good agreement with the data, showing that symmetry properties dominate over differences in the internal quark-gluon structure of different states. If the nucleon is probed

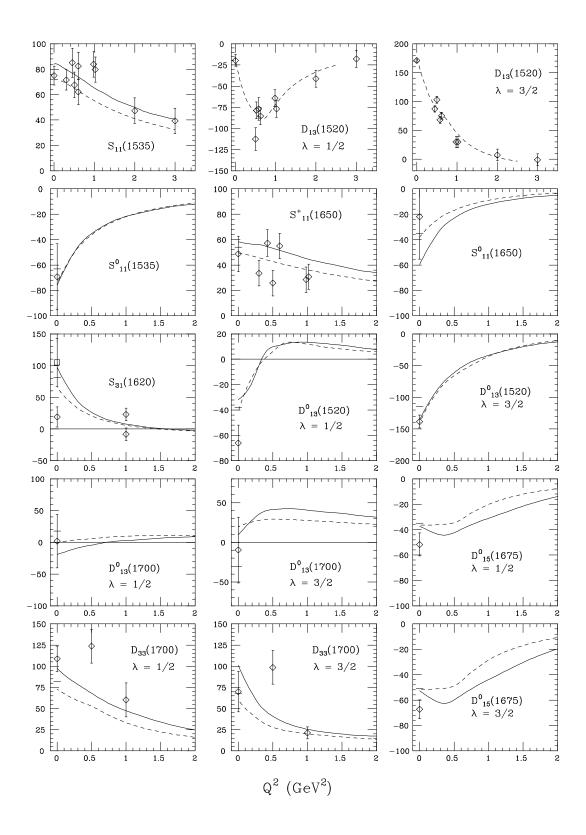


Figure 4. Single Quark Transition Model predictions for states belonging to the  $SU(6)\otimes O(3)$  multiplet, discussed in the text.

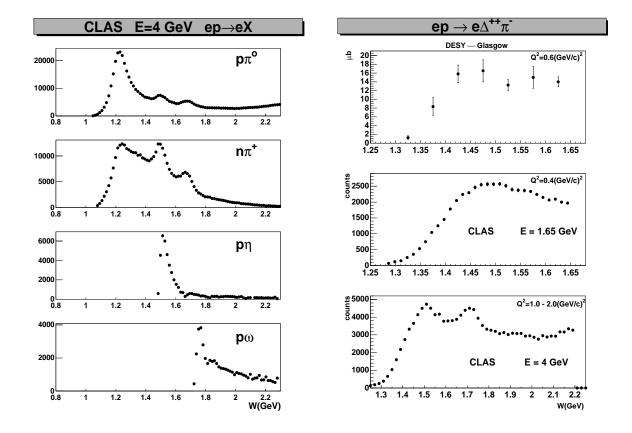


Figure 5. Yields for various channels measured with CLAS at JLAB. The statistical error bars are smaller than the data points.

Figure 6. Yields for the channel  $\Delta^{++}\pi^{-}$  measured with CLAS at different  $Q^2$  compared to previous data from DESY.

at smaller distances, we expect symmetry properties to become less important.

The current situation is shown in Figure 4, where the SQTM amplitudes for the transition to the [70, 1<sup>-</sup>] supermultiplet have been extracted from the measured amplitudes for  $S_{11}(1535)$  and  $D_{13}(1520)$ . Predictions for other states belonging to the same multiplet are shown in the other panels [27]. The lack of accurate data for most resonances prevents a sensitive test of the SQTM for space-like photons.

The goal of the experimental N\* program at JLAB with the CLAS detector is to provide data in the entire resonance region, by measuring many channels in a large kinematic range, including various polarization observables. The yields of several channels, recorded simultaneously in CLAS, are shown in Figure 5 and Figure 6. Resonance excitations seem to be present in all channels. The graphs also illustrate how the various channels have sensitivity to different resonance excitations. For example, the  $\Delta^{++}\pi^{-}$  channel clearly shows resonance excitation near 1720 MeV while single pion production is more sensitive to a resonance near 1680 MeV [31]. The  $p\omega$  channel seems to show resonance excitation near threshold, similar to the  $p\eta$  channel. No resonance has been observed in this channel so far. The single pion channels are essential for an accurate determination of many transition amplitudes. For the first time,  $n\pi^{+}$  electroproduction has been measured

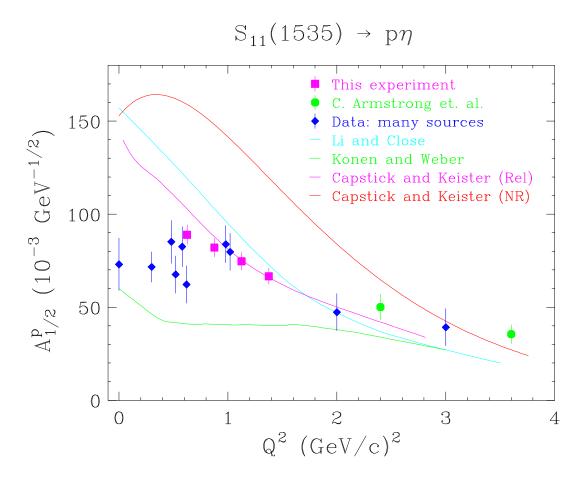


Figure 7. Transverse photocoupling amplitude for the  $\gamma_v p N^*(1535)$  transition. The full squares at lower  $Q^2$  are preliminary CLAS data [28]. The full circles at large  $Q^2$  are data from a previous JLAB experiment [29]

throughout the resonance region, and in a nearly complete angle range.

New data have been obtained in the channel  $ep \to ep\eta$ . The  $p\eta$  channel selects isopin 1/2 resonances, and is particularly sensitive to the  $N^*(1535)$  state. Preliminary data from CLAS are shown in Figure 7. The data confirm the previously observed, and not fully understood, slow fall-off of the resonance transition form factor with  $Q^2$ . However, at low  $Q^2$ , the trend of the data favors a larger photocoupling amplitude for that state than the  $Q^2 = 0$  data point indicates. One should note that meson cloud effects can give different results for  $N\pi$  or  $N\eta$  channels unless the analysis properly accounts for rescattering and coupled channel effects.

For the first time the  $N\pi\pi$  channel has been measured with high statistics in photo-and electroproduction. Using an isobar model approach one can study contributions of  $N\rho$  and  $\Delta\pi$  decay channels [31] which are especially sensitive to the so-called missing resonances. Figure 6 illustrates the vast improvement in data volume for the  $\Delta^{++}\pi^{-}$  channel. The top panel shows DESY data taken more than 20 years ago. The other two panels show samples of the data taken so far with CLAS. At higher  $Q^2$ , resonance structures, not seen

# $d\sigma/d\theta$ (ep -> $e^{I}p\omega$ ) (very preliminary)

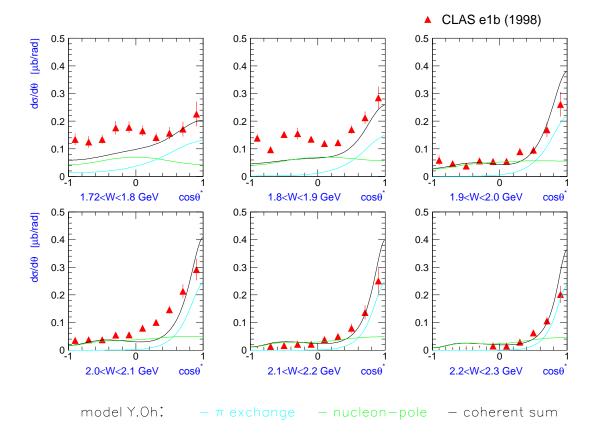


Figure 8. Electroproduction of  $\omega$  mesons for different W bins, and in a  $Q^2$  range  $\approx 1.0$  -  $2.0~{\rm GeV^2}$  [33]. The deviation of the  $\cos\theta$  -distribution from a smooth fall-off for the low W bin suggests significant s-channel resonance production. Model calculation without resonance contributions [34].

before in this channel, are revealed.

## 5. MISSING QUARK RESONANCES

With large acceptance detectors such as CLAS more complex final states can be studied than has been possible in the past. This will allow us to systematically tackle a long-standing problem, the so-called "missing resonances". These are states predicted in the symmetric  $|Q^3\rangle$  model to populate the mass region around 2 GeV but have not been seen in  $\pi N$  elastic scattering, which is our main source of information on the nucleon excitation spectrum. These states may thus be either absent from the spectrum, or they may not couple to the  $N\pi$  channel. It is important to search for at least some of these states since their absence from the spectrum would be evidence that SU(6) symmetry is strongly violated in light-quark baryon spectroscopy. Other symmetry scheme have been considered. For example, the observed clustering of baryon states may reflect an

underlying Lorentz-isospin group symmetry  $O(1,3) \otimes SU(2)_I$ , as discussed recently in ref. [30]. The number of states is significantly reduced in this latter approach compared to the symmetric model, more in accordance with the observed spectrum. As these possibilities reflect very different underlying baryon structure models, it is extremely important to search for states that are predicted in one scheme but not in the other.

How do we search for states that do not couple to the  $\pi N$  channel? Channels which are predicted to couple strongly to "missing" states are  $N(\rho,\omega)$  or  $\Delta\pi$ . Some may also couple to KY or  $p\eta'$  [32]. Some of the "missing" states may also couple to  $N\gamma$ , and should therefore be excited in photo- or electroproduction experiments.

Figure 8 shows very preliminary data from CLAS in the  $p\omega$  channel. The process is expected to be dominated by t-channel  $\pi^o$  exchange with strong peaking at forward  $\omega$  angles, or low t, and a monotonic fall-off at large t. The data show clear deviations from the smooth fall-off for the W range near 1.9 GeV, where some of the "missing" resonances are predicted, in comparison with the high W region. Although indications for resonance production are strong, analysis of more data and a partial wave study are needed before definite conclusions can be drawn.

CLAS has collected  $3 \cdot 10^5 p\eta'$  events in photoproduction. Production of  $\eta'$  has also been observed in electron scattering for the first time with CLAS. This channel may provide a new tool in the search for missing states as well [25]. The quark model predicts two resonances in this mass range with significant coupling to the  $N\eta'$  channel [32].

 $K\Lambda$  or  $K\Sigma$  production may yet be another source of information on resonant states. Previous data show some evidence for resonance production in these channels [35]. New data with much higher statistics are being accumulated with the CLAS detector, both in photo- and electroproduction. Analysis of the  $\Lambda$  polarization provides additional information sensitive to resonance excitations.

## 6. OUTLOOK

The experimental effort with CLAS at Jefferson Lab will provide the community with a wealth of data in the first decade of this new millennium to address many open problems in hadronic structure in the domain of nucleon resonances and at intermediate distances. The experimental effort must be accompanied by a significant theoretical effort to translate this into real progress in our understanding of the complex regime of strong interaction physics. The region of nucleon resonances is of special interest as it represents a domain where different degrees of freedom, from hadronic, to constituent quarks, to valence quarks, overlap. On the one hand, this provides a challenge to theory, on the other hand an opportunity, as only under such circumstances can there be a realistic possibility for a unified description of hadron structure from small to large distances.

### REFERENCES

- 1. N. Isgur and G. Karl; Phys. Lett. B72:109 (1977), Phys. Rev. D23, 817 (1981)
- 2. N. Isgur, hep-ph/9904494, (1999)
- 3. E. Golowich, E. Haqq, G. Karl, Phys. Rev. D28, 160(1983)
- 4. L.S. Kisslinger, Z.P. Li, Phys.Rev.D51:5986-5989,1995
- 5. P. Page, Talk at NSTAR2000, Newport News, Virginia, Feb. 16-19, 2000

- V.D. Burkert and Zh. Li, Phys. Rev. D47, 46 (1993); V.D. Burkert and B.L. Ioffe, Phys. Lett. B296, 223 (1992); V.D. Burkert and B.L. Ioffe, J. Exp. Theo. Phys. 78, 619 (1994)
- 7. E.D. Bloom and F.J. Gilman, Phys. Rev. D4, 2901(1970)
- 8. B. A. Mecking, Invited talk at BARYONS '98, Bonn, September 1998.
- 9. C.E. Carlson, Phys. Rev. D34,2704(1986)
- 10. V.D. Burkert, L. Elouadrhiri, Phys. Rev. Lett. 75, 3614 (1995)
- 11. V. Frolov et al., Phys. Rev. Lett.82, 45 (1999)
- 12. Shin-Nan Yang, Talk presented at NSTAR2000, Newport News, Virginia, Feb. 16-19, 2000
- 13. T. Sato and T.-S.H. Lee, Phys. Rev. C54, 2660 (1996); T.-S.H. Lee, private communications (2000)
- 14. A. Silva, D. Urbano, T. Watabe, M. Fiolhais, K. Goeke, Nucl. Phys. A675, 637, 2000
- 15. N. Isgur, G. Karl, R. Koniuk, Phys. Rev. D25:2394, 1982
- 16. L.C. Smith, Talk at NSTAR2000
- 17. L. Elouadrhiri, these proceedings.
- 18. C. Gerhardt, Z. Phys. C4, 311 (1980)
- 19. Z.P. Li, V.D. Burkert, Zh. Li, Phys. Rev. D46, 70(1992)
- 20. F. Cano and P. Gonzales, Phys.Lett.B431:270-276,1998
- 21. S. Capstick and B. Keister, Phys. Rev. D51, 3598 (1995)
- 22. Y.B. Dong, K. Shimizu, A. Faessler, A.J. Buchmann, Phys. Rev. C60 (1999)
- 23. S. Krewald et al., Proceedings of NSTAR2000
- 24. S. Capstick, private communications
- 25. B. Ritchie, Talk at NSTAR2000
- 26. A.J. Hey, J. Weyers, Phys. Letts. 48B, 69(1974)
- 27. V.D. Burkert, Czech. J. Phys. Vol46, 627 (1996); V.D. Burkert, Int. J. Mod. Phys. E1:421-464(1992)
- 28. J. Mueller, Talk presented at BARYONS'98, Bonn, September 1998; S. Dytman, J. Mueller, private communications (2000)
- 29. C.S. Armstrong et al., Phys. Rev. D60, 52004 (1999)
- 30. M. Kirchbach, Mod. Phys. Lett. A12, 3177 (1997)
- 31. M. Ripani, Talk at NSTAR2000
- 32. S. Capstick and W. Roberts, Phys. Rev. D49, 4570(1994)
- 33. H. Funsten and F.J. Klein, private communications
- 34. Y. Oh and T.-S.H. Lee, to be published and private communications (2000)
- 35. C. Bennhold, Talk at NSTAR2000